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Starlight and Sandstorms: Mass Loss Mechanisms on the AGB

Susanne Höfner

Department of Physics & Astronomy, Uppsala University, Sweden

Abstract. There are strong observational indications that the dense slow winds of cool luminous AGB stars are driven by radiative pressure on dust grains which form in the extended atmospheres resulting from pulsation-induced shocks. For carbon stars, detailed models of outflows driven by amorphous carbon grains show good agreement with observations. Some still existing discrepancies may be due to a simplified treatment of cooling in shocks, drift of the grains relative to the gas, or effects of giant convection cells or dust-induced pattern formation. For stars with $C/O < 1$, recent models indicate that absorption by silicate dust is probably insufficient to drive their winds. A possible alternative is scattering by Fe-free silicate grains with radii of a few tenths of a micron. In this scenario one should expect less circumstellar reddening for M- and S-type AGB stars than for C-stars with comparable stellar parameters and mass loss rates.

“It is a truth universally acknowledged, that an evolved cool giant star must develop a wind. However little known the parameters of such a star may be on its first entering the red giant stage, this truth is so well fixed in the minds of stellar astronomers, that it is considered as the rightful member of some one or other class of mass-losing long-period variables.”

— Introduction to a fictitious manuscript entitled ‘Winds of Cool Giants: Properties and Prejudices,’ adapted from a classical text by Austen (1813)

1. Introduction

Winds of AGB stars can be studied observationally with a variety of methods, ranging from classical spectroscopy and photometry through direct imaging to interferometric techniques. These various methods are complementary in the sense that they can provide information about stellar winds on very different spatial and temporal scales, as well as independent ways of studying a particular effect. From photometric time series we can deduce crucial information about stellar pulsation and possibly dust formation; high-resolution spectra and IR multi-wavelength interferometry allow quantitative insights into the dynamics and structure of the regions where wind formation takes place; and imaging of circumstellar envelopes on global scales holds clues to the mass loss history of individual stars and their interaction with the surrounding interstellar medium. The general picture derived from observations is that of largely spherical, but probably clumpy and time-dependent, outflows with typical velocities of 5–30 km/s and mass loss rates of about 10^{-7} to $10^{-5} M_{\odot}/\text{yr}$.

A thorough physical understanding of the mass loss phenomenon and detailed quantitative models of stellar winds are required to understand both AGB stars in their

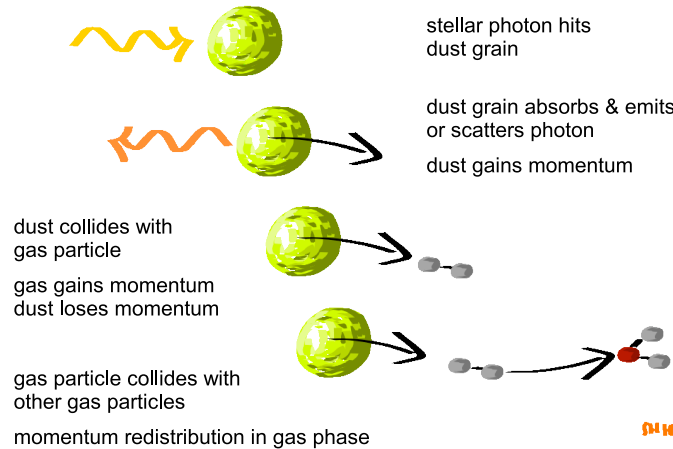


Figure 1. Microphysics of dust-driven winds: Dust grains acquire momentum from stellar photons and transfer it to the surrounding gas via collisions.

own right, and their role in the bigger picture of the cosmic matter cycle. Reliable mass loss rates, dust production rates, and consistent synthetic spectra are necessary ingredients for population synthesis, modelling the chemical evolution of galaxies, and gauging the contribution of AGB stars to the integrated light and intrinsic reddening of distant galaxies.

2. Basic Scenarios and Wind Mechanisms

A common feature of the most evolved cool giants is the presence of dust in their outer atmospheres and winds, often inferred from photometry (circumstellar reddening, IR excess), and sometimes more specifically from the detection of spectral features characteristic of particular species of dust grains (see, e.g., Waters, this volume). In principle, the grains could just be a by-product of the outflows, condensing from the cooling gas as it moves away from the stellar surface. It has, however, been suspected for a long time that radiative acceleration of dust is an important ingredient of the wind driving mechanism (see Fig. 1; for a historical overview see, e.g., Habing & Olofsson, 2004).

The formation and survival of dust particles requires temperatures below the stability limit of the respective condensate. As the temperature of a grain will be mostly determined by its interaction with the radiation field, it cannot exist closer to the star than the distance where its radiative equilibrium temperature is equal to the condensation temperature T_c of the grain material. Assuming a Planckian stellar radiation field, and a power law for the grain absorption coefficient $\kappa_{\text{abs}} \propto \lambda^{-p}$ in the relevant wavelength range (i.e. around the flux maximum of the star), the condensation distance R_c can be estimated by $R_c/R_* = 0.5 (T_c/T_*)^{-(4+p)/2}$ (see, e.g., Lamers & Cassinelli, 1999).

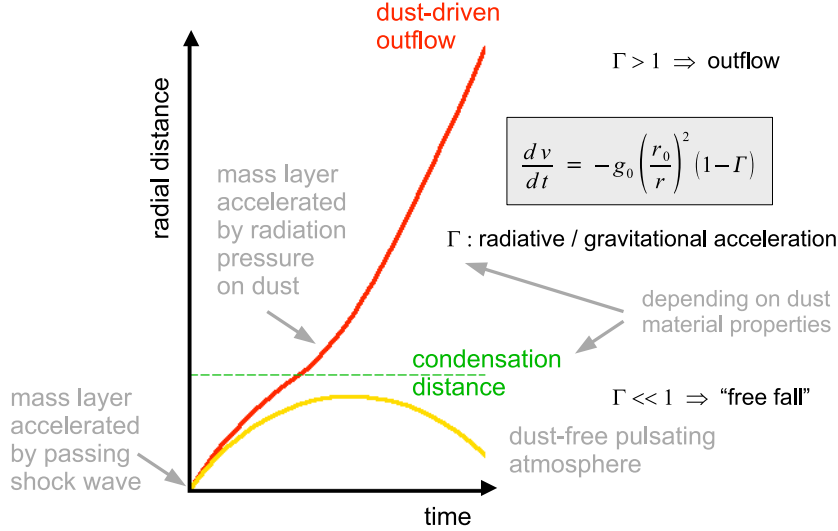


Figure 2. Schematic picture of the dynamics of mass layers, based on a simple toy model taking only gravity and radiative acceleration into account (see Höfner, 2009, for details and typical numbers).

For amorphous carbon grains with $T_c \approx 1500$ K and $p \approx 1$ we obtain $R_c/R_* \approx 2 - 3$ which compares well with detailed models.

At this point, the question arises how the dust-free gas can bridge the gap between the stellar photosphere and the condensation distance. Some early models, assuming a gradual transition from a nearly hydrostatic atmosphere to a steady, time-independent outflow, invoked Alfvén waves (e.g. Hartmann & MacGregor, 1980) or acoustic wave pressure (e.g. Pijpers & Hearn, 1989) to start or even drive the winds. Such mechanisms may be important for stars with parameters that exclude dust-driven winds, but for cool AGB stars with large-amplitude pulsations the combination of atmospheric levitation due to shock waves and radiative acceleration of dust grains seems to be more effective. The shock waves triggered by the pulsation periodically accelerate the upper atmospheric layers outwards, intermittently creating dense environments in their wakes. The layers follow approximately ballistic trajectories which may take them above the condensation distance if the initial velocity is high enough. There, dust condensation can occur and radiation pressure may accelerate the dust-gas mixture outwards (see Fig. 2). This scenario is supported by spectroscopic and interferometric observations of extended, dynamical molecular layers around AGB stars (see, e.g., contributions by Ireland, Wittkowski et al., Ruiz-Velasco et al., all this volume; Tej et al., 2003; Weiner, 2004; Sacuto et al., 2011).

Time-dependent wind models investigating the effects of pulsation and radiative acceleration of dust were pioneered by Wood (1979) and Bowen (1988), using a

simple parameterized description for the dust opacity, followed by studies including time-dependent grain growth for C stars (e.g. Fleischer et al., 1992; Höfner & Dorfi, 1997). Detailed models based on the ‘pulsation-enhanced dust-driven wind scenario’ have been quite successful in reproducing typical mass loss rates and wind velocities, as well as photometry and spectra at various resolutions (e.g. Le Bertre & Winters, 1998; Winters et al., 2000; Andersen et al., 2003; Gautschy-Loidl et al., 2004; Nowotny et al., 2010, and this volume; and Eriksson et al., this volume). While an earlier generation of models with grey radiative transfer was sufficient to explain the main characteristics of heavily dust-enshrouded C-rich AGB stars, it is necessary to combine frequency-dependent radiative transfer (including gas and dust opacities) with time-dependent hydrodynamics and non-equilibrium dust formation, in order to obtain realistic results for objects with less optically thick envelopes (e.g. Höfner et al., 2003).

Ironically, it was the introduction of non-grey dynamical models which led to a crisis regarding the role of dust as a wind driver for M-type AGB stars. In contrast to C-type objects (where the excess carbon not bound in CO can condense into amorphous carbon grains which can drive outflows), the more common AGB stars with $C/O < 1$ have no abundant chemical elements which can form dust on their own sufficiently close to the stellar surface. Based on relative abundances, chemical properties, and thermodynamical conditions, it is commonly assumed that olivine- and pyroxene-type Mg-Fe silicates are the main dust species in M-type stars (e.g. Gail & Sedlmayr, 1999; Ferrarotti & Gail, 2001; Gail, 2003, Andersen, this volume; Waters, this volume). Using detailed non-grey dynamical models, Woitke (06b) demonstrated that silicate grains have to be virtually Fe-free at distances corresponding to the wind acceleration zone, leading to insufficient radiative pressure due to low absorption cross sections. The core of the issue can be understood using the simple estimate for the condensation distance R_c given above: For silicates, $T_c \approx 1000$ K and p is strongly dependent on the Mg/Fe ratio. Considering olivine-type material, grains with about equal amounts of Fe and Mg lead to $p \approx 2$ for the absorption coefficient of small grains and, consequently, to $R_c/R_* > 10$, whereas iron-free particles with a corresponding value of $p \approx -1$ can form at typically $R_c/R_* \approx 2 - 3$ (see Fig. 3; comparable numbers hold for pyroxene-type particles).

According to models by Höfner (2008) this problem can be resolved if conditions in the extended atmosphere allow Fe-free silicate grains to grow to sizes $> 0.1 \mu\text{m}$ because scattering will contribute significantly to the radiative pressure for grains with radii comparable to wavelengths near the stellar flux maximum. Various observational tests of this scenario are currently being performed as described in the following section. In this context, it should be noted that the recent C-star wind model grid by Mattsson et al. (2010) indicates that the amorphous carbon grains forming in these stars may also be bigger than previously assumed. In this case, scattering on grains may contribute to the radiative pressure, possibly affecting winds close to the thresholds for dust-driven mass loss (see Mattsson & Höfner, this volume). For typical winds of C stars, however, grain size will not be a decisive factor, as even small amorphous carbon particles are efficient absorbers and can easily drive outflows.

3. A Closer Look: Differences between M- and C-type AGB Stars

From the early days of stellar spectroscopy, cool giants could be sorted into two major groups, according to the relative abundances of C and O in their atmospheres and

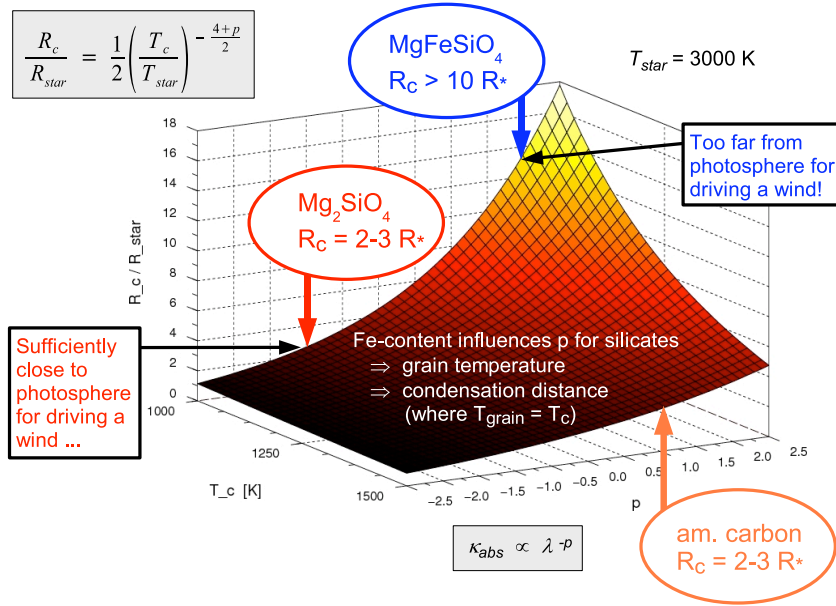


Figure 3. Condensation distance R_c (in units of the stellar radius R_*) as a function of the power law index of the absorption coefficient p for a range of condensation temperatures T_c (assuming a stellar temperature of $T_* = 3000$ K; see text for details).

the resulting distinct differences in molecular chemistry.¹ With the advent of space-based IR surveys, however, it became evident that this chemical difference even leads to profound effects in the circumstellar envelopes. Using photometry (e.g. the classical IRAS 2-colour diagram), AGB stars can be sorted both according to current mass loss rates and mass loss history (detached shells), as well as by the C/O ratio. C-type AGB stars tend to show much more pronounced circumstellar reddening at visual and NIR wavelengths than M-type objects with comparable stellar parameters. In view of the clear spectroscopic and photometric distinctions between M- and C-type objects, it is interesting to note that the average wind properties of M-, S-, and C-type AGB stars are very similar (e.g. Ramstedt et al., 2006).

For cool luminous carbon stars there is strong evidence that their winds are driven by radiation pressure on amorphous carbon grains. Models based on the pulsation-enhanced dust-driven wind scenario (discussed in the previous section) have been tested against a range of observations and are now used for the interpretation of observational data of individual stars, and applied to stellar evolution (e.g. Schröder et al., 2003).

¹This dichotomy is caused by the high bond energy of CO which leads to an almost complete blocking of the less abundant of the two elements in CO. In C-type objects (C/O > 1) the excess carbon can form C-bearing molecules and amorphous carbon grains, while M-type stars (C/O < 1) feature O-bearing species in their molecular chemistry and dust.

For M-type AGB stars, in the light of the detailed models by Woitke (06b) it seems unlikely that winds can be driven by radiative pressure on Fe-bearing silicate grains, in contrast to previous assumptions. As discussed in Sect. 2, the inclusion of Fe in olivine- and pyroxene-type particles² leads to high grain temperatures and, consequently, condensation distances well beyond the wind acceleration zone (see Fig. 3). Fe-free olivine- and pyroxene-type grains which can form sufficiently close to the stellar photosphere, on the other hand, have low absorption cross sections in the critical wavelength range near the stellar flux maximum (around $1\ \mu\text{m}$) which are insufficient for driving an outflow.

A possible solution of this problem is scattering: If conditions in the extended atmospheres allow such grains to grow into the size range of about $0.1 - 1\ \mu\text{m}$, scattering becomes dominant over absorption by several orders of magnitude, opening up the possibility of stellar winds driven by scattering on Fe-free grains. Detailed frequency-dependent dynamical models by Höfner (2008) show that forsterite grains may well reach this critical size range, leading to outflows with combinations of mass loss rates and wind velocities that compare well with observations (see Fig. 5 in Höfner, 2009). First tests of synthetic spectra and photometric colours resulting from these models show good agreement with observations (see Fig. 1 in Bladh et al., this volume), and an ongoing study of self-consistent M-type wind models with parameterized dust opacities should allow us to draw further conclusions about what relative levels of true absorption and scattering by dust are compatible with observed SEDs (Bladh et al., in prep.). Furthermore, new spectro-interferometric data probing the outer atmosphere and inner wind region of RT Vir shows a clear transition from a purely molecular to a dusty regime which may give us direct indications of condensation distances and grain types (see Olofsson et al., this volume).

If scattering on Fe-free silicate grains turns out to be a major driving mechanism in dusty M-type (and maybe S-type) AGB stars, the levels of true absorption by dust (and, consequently, circumstellar reddening), as well as the dynamical response to dust formation (the resulting acceleration) may be quite different from that in C-type AGB stars with similar stellar parameters. These effects might be related to, for example, recently discovered qualitative differences in the phase-to-phase and cycle-to-cycle variations (or lack thereof) in IR interferometric data (see Karovicova et al., and Ohnaka, this volume).

4. Open Questions, Conclusions and Outlook

Current dust-driven wind models focus on the chemical composition and optical properties of dust grains while often using the simplifying assumptions of complete momentum coupling and position coupling for the all-important interaction of dust and gas. In reality, the grains will move faster than the gas, and this drift can affect grain growth and wind dynamics (e.g. Sandin & Höfner, 2004), as well as the large-scale structure of the CSE (Simis et al., 2001). Another physical feature of present models which may need further investigation is strong radiative cooling behind shocks due to high molecular opacities, corresponding to chemical equilibrium and LTE conditions. Less efficient

²The presence of such dust particles can be inferred both from observations of dust features in the IR (e.g. Waters, this volume), and from gas kinetic arguments (e.g. Gail, 2003). Notably, under chemical equilibrium conditions the Mg-rich end members of the olivine and pyroxene sequences should be dominant.

cooling could open the possibility of ‘pulsation-driven dust-enhanced winds’ as discussed by Willson (2000). Furthermore, considering the crucial role of atmospheric dynamics for the wind mechanism, both self-excited pulsation models (e.g. Wood & Arnett, this volume), and a detailed analysis of time-dependent phenomena in atmospheres and winds (e.g. Dreyer et al., this volume) should be high on the agenda of modellers.

The ‘pulsation-enhanced dust-driven wind scenario’, discussed in some detail in this review, seems to be the most promising explanation for the high mass loss rates of the most evolved cool, luminous AGB stars, but there are natural limits for this mechanism. High stellar temperatures lead to large condensation distances, and low luminosity-to-mass ratios may require more radiative acceleration than can be provided by grain radiative cross sections. For low metallicities, the availability of condensable material may be another issue. Here, again, significant differences between C- and M-type stars should exist, since carbon stars produce the main dust-forming element by nucleosynthesis, whereas M-type objects basically have to rely on the supply of potentially dust-forming elements with which they started out. Therefore, mass loss should show a much stronger dependence on metallicity for M-type AGB stars than for their C-rich counterparts (e.g. Mattsson et al., 2008) which seems to fit with observed trends (e.g. Lagadec et al., Sloan et al., this volume).

Focusing on the microphysics of the driving mechanism, it is easy to overlook that observations show evidence of deviations from homogeneous, spherically symmetric outflows at various scales, e.g. clumpy structures, large-scale asymmetries of the CSE, and structures possibly due to focusing of wind material by close binaries (Kim & Taam, Mohamed & Podsiadlowski, this volume). Whether any of these phenomena are directly related to or give constraints on the mass loss mechanisms is unclear at present. 3D ‘star-in-a-box’ models of stellar convection and its effects on dust formation (Freytag & Höfner, 2008) or studies of dust-induced pattern formation in CSEs (Woitke, 06a) are few and far between due to the considerable numerical effort involved and various technical difficulties.

Last but not least it should be mentioned that indications of stellar winds are seen for AGB stars falling outside the parameter region where present models predict dust-driven mass loss (e.g. Wachter et al., 2008; Mattsson et al., 2010), challenging our current understanding of mass loss mechanisms. Where both dust and shock waves fail as wind drivers, magnetic fields and Alfvén waves might play a role in accelerating the observed outflows (see, e.g., Hartmann & MacGregor, 1980; Airapetian et al., 2010; Vlemmings, 2011).

Having started this review with a fictitious quotation, it may be appropriate to end it with a real one. Pratchett (1993) claims that “Of all the forces in the universe, the hardest to overcome is the force of habit. Gravity is easy-peasy by comparison.” Translating this to the present context, we may conclude that AGB stars clearly manage to drive winds, but gaining a comprehensive, quantitative understanding of the relevant mechanisms may require thinking outside the current computational box.

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